Beam-helicity asymmetry measurements in the Virtual Compton Scattering reaction in the $\gamma^* N \to \Delta$ transition at $Q^2 = 0.20$ (GeV/c)^2

N.F. Sparveris[1*†], P. Achenbach[2], C. Ayerbe Gayoso[2], D. Baumann[2], J. Bernauer[2], A.M. Bernstein[4], R. Böhm[2], D. Bosnar[5], T. Botto[4], A. Christopoulou[1], D. Dale[6‡], M. Ding[2], M.O. Distler[2], L. Doria[2], J. Friedrich[2], A. Karabarbounis[1], M. Makek[5], H. Merkel[2], U. Müller[2], I. Nakagawa[3], R. Neuhausen[2], L. Nungesser[2], C.N. Papanicolas[1], B. Pasquini[8], A. Piegsa[2], J. Pochodzalla[2], M. Potokar[7], M. Seimetz[2], S. Širca[7], S. Stave[4§], S. Stiliaris[1], Th. Walcher[2] and M. Weis[2]

[1]*Institute of Accelerating Systems and Applications and Department of Physics, University of Athens, Athens, Greece*
[2]*Institut fur Kernphysik, Universität Mainz, Mainz, Germany*
[3]*Radiation Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[4]*Department of Physics, Laboratory for Nuclear Science and Bates Linear Accelerator Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[5]*Department of Physics, University of Zagreb, Croatia*
[6]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40206 USA*
[7]*Institute Jožef Stefan, University of Ljubljana, Ljubljana, Slovenia and*
[8]*Dipartimento di Fisica Nucleare e Teorica, Università degli Studi di Pavia, and INFN, Sezione di Pavia, Pavia, Italy*

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We report on new beam-helicity asymmetry measurements (A_h) of the H($\vec{e}, e'p$)γ reaction in the Δ(1232) resonance at $Q^2 = 0.20$ (GeV/c)^2. The measurements were performed at MAMI and were carried out simultaneously with the measurement of the H($\vec{e}, e'p$)π^0 reaction channel. It is the lowest Q^2 for which the A_h for the virtual Compton scattering (VCS) reaction has been measured in the first resonance region. The measured asymmetries have been compared and have been found to be well described by dispersion-relation (DR) calculations for VCS. The sensitivity of the data to the Generalized Polarizabilities (GPs) of the proton and to the amplitudes associated with the nucleon excitation to the Δ(1232) has been explored through the DR formalism. The measured asymmetries have been found to exhibit a much higher sensitivity to the GPs while it is suggested that future measurements of higher statistical precision will offer stronger constraints to theoretical calculations and will provide valuable insight towards a more complete understanding of the GPs of the proton and of the πN amplitudes.

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A fundamental question of nuclear physics is the description of the internal structure of the nucleon. While the small distance structure of the nucleon is adequately described by point-like quarks and gluons, its description at larger distance can involve both quark and baryon-meson degrees of freedom. The study of the structure of the nucleon can be pursued by the exploration of a number of complementary reactions and through the measurement of various type of observables. Polarization observables has been proven a very valuable tool towards this direction in the recent years. Such observables have been explored at higher energies to access the generalized parton distributions through the exclusive deep virtual compton scattering reaction and for the study of the transverse spin structure of the nucleon in semi-inclusive deep inelastic scattering while at lower energies they can provide significant sensitivity to various amplitude interferences through the exploration of pion- and photon-electroproduction reactions.

One of the reaction mechanisms sensitive to the electromagnetic structure of the nucleon is the Virtual Compton Scattering (VCS) reaction. VCS off the proton refers to the reaction $\gamma^* p \to e\gamma p$, which is accessed experimentally through photon electroproduction $ep \to ep\gamma$, and is the coherent sum of the Compton process and the Bethe-Heitler (BH) process. The BH process refers to the photon emission by the incoming or outgoing electron and it adds coherently to the VCS amplitude. The Compton amplitude decomposes into a Born term, characterized by a proton in the intermediate state, and a Non-Born term containing all other intermediate states; the Born part is given in terms of nucleon ground state properties and the non-Born part contains all nucleon excitations and meson-loop contributions. The BH and Born amplitudes are entirely calculable, with the proton electromagnetic form factors as inputs.

The VCS has been proven in the recent years a valuable reaction, complementary to elastic scattering and to pion-production, which has provided new insights on the nucleon internal structure. Previous experiments, both below and above the pion threshold, have focused on the study of the generalized polarizabilities (GPs) of the proton [1, 2, 3, 4] and the exploration of the res-

*current address: Massachusetts Institute of Technology
†corresponding author, e-mail address: sparveri@jlab.org
‡current address: Idaho State University, Department of Physics, Pocatello, Idaho 83209, USA
§current address: Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708, USA

onant amplitudes associated with the proton excitation to the $\Delta(1232)$ resonance [5], through cross section measurements, as well as on the study of the imaginary part of the VCS amplitude through beam helicity asymmetry (A_h) measurements [6]. In the present work we present new beam helicity asymmetry A_h measurements in the $\Delta(1232)$ resonance region and at four-momentum transfer of $Q^2 = 0.20$ (Gev/c)^2.

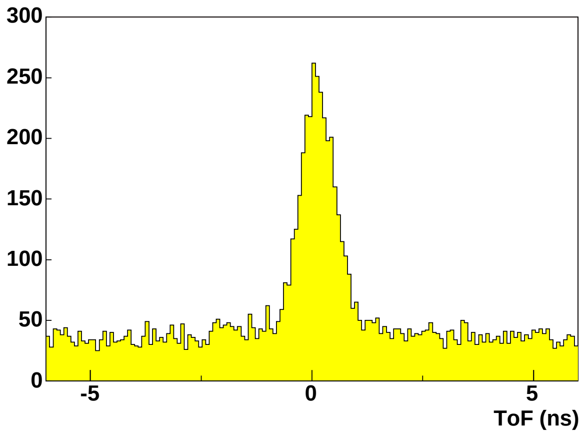

FIG. 1: The coincidence time spectrum for the H$(\vec{e}, e'p)\gamma$ reaction.

In order to measure the beam helicity asymmetry A_h in the $\vec{e}p \rightarrow ep\gamma$ process a longitudinally polarized electron beam has to be utilized while the measurements have to be performed above the pion threshold, where the VCS amplitude acquires an imaginary part due to the coupling to the πN channel. Single polarization observables, which are proportional to the imaginary part of the VCS amplitude, become nonzero above the pion threshold. The A_h also requires measurements at out-of-plane values of ϕ, where ϕ is the reaction azimuthal angle with respect to the momentum transfer direction and the scattering plane, due to the sinϕ type of dependence of the asymmetry. The beam helicity asymmetry is defined as $A_h = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$ where σ^+ and σ^- designate the photon electroproduction cross-section with beam-helicity state + and -, respectively. Since the BH and Born-VCS contributions are purely real, the A_h is due to the interference of the imaginary part of the non-Born VCS amplitude with the real BH+VCS amplitude. After development, one obtains in the nominator the sum of a pure VCS contribution and a VCS-BH interference term which has the effect to enhance the asymmetry. In the case of A_h the interference of VCS with BH is desirable since it serves as an amplifier of the measured asymmetry; the A_h would be much smaller in the absence of the BH process and the presence of VCS alone.

By measuring A_h we can acquire information on the absorptive part of the VCS amplitude and on the relative phase between the VCS amplitude and the BH contribution [7] aiming to a good description of the VCS

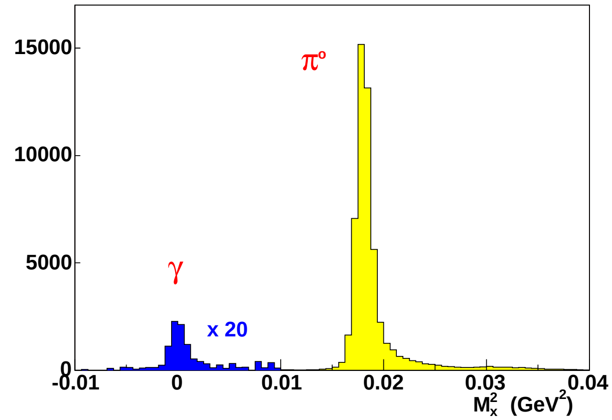

FIG. 2: The derived missing mass spectrum, plotted as a function of the square of missing mass shows the superb resolution achieved, essential to isolating the small photon decay branch of the $\Delta(1232)$ Resonance. Channels for $M_x^2 < 0.01 GeV^2$ have been multiplied by a factor of twenty.

amplitude and to the understanding of its Q^2 dependence. Through the A_h measurements one can test the theoretical models mostly towards their prediction of the imaginary part of VCS. Towards this direction we exploit the Dispersion-Relation (DR) calculation [8, 9] for virtual compton scattering. In this model the VCS non-Born contribution is given in terms of dispersive integrals relating the real and imaginary parts of the amplitude. The imaginary part is calculated, through the unitarity relation, from the scattering amplitudes of electro- and photo-production on the nucleon, taking into account the dominant contribution from πN intermediate states. The DR model has two free parameters, Λ_α and Λ_β, related to the dipole electric and magnetic GPs, respectively, while the amplitudes for $\gamma^{(*)}p \rightarrow \gamma\pi$ entering the unitarity relation are taken from the MAID-2007 [10] model. A measurement of A_h offers a strong cross-check of the dispersion formalism for VCS.

The experiment was performed at the Mainz Microtron MAMI utilizing an 855 MeV longitudinally polarized electron beam with an average beam current of 25 μA employed on a 5 cm long liquid-hydrogen target. The longitudinal beam polarization was $\approx 75\%$ throughout the experiment. The A1 magnetic spectrometers [11] were used for the proton and electron detection; Electrons and protons were detected in coincidence with spectrometers A and B respectively. The detector package in each spectrometer includes a set of vertical drift chambers for particle tracking and scintillator detectors for timing and particle identification measurements while a Cerenkov counter was also used for the electron identification. The H$(\vec{e}, e'p)\gamma$ reaction was performed at $Q^2 = 0.20$ (GeV/c)^2 and at $W = 1210$ MeV. The measurement of the H$(\vec{e}, e'p)\gamma$ reaction channel was performed simultaneously with the measurement of the H$(\vec{e}, e'p)\pi^0$ chan-

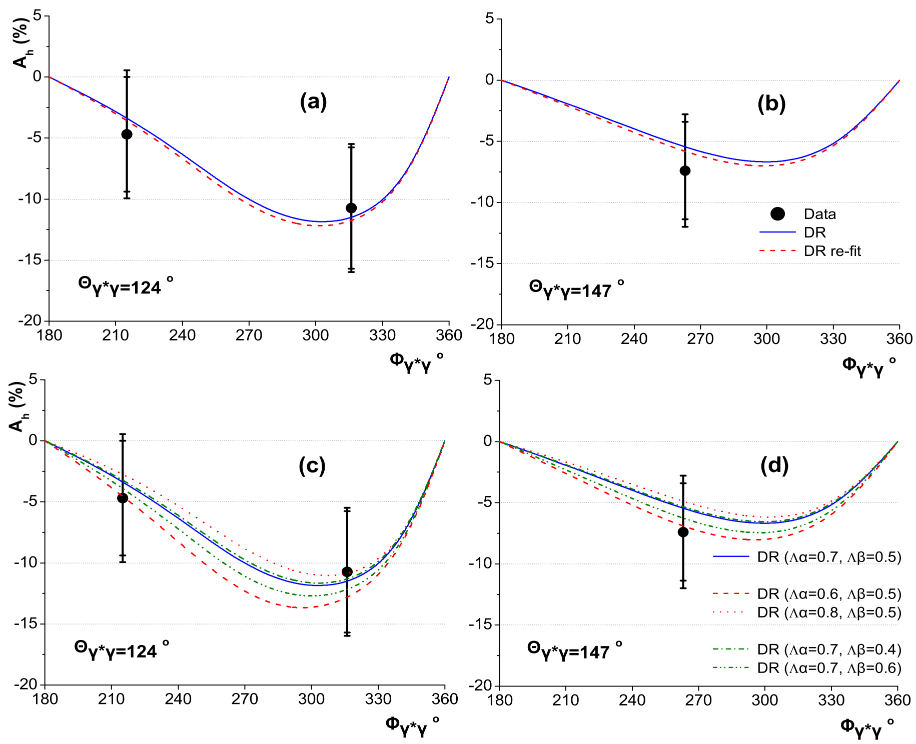

FIG. 3: The measured beam-helicity asymmetries A_h as a function of $\phi_{\gamma^*\gamma}$. The errors correspond to the statistical and the total experimental uncertainties. The DR calculation is presented along with the data. At the top panels the sensitivity to the πN amplitudes is explored (with the re-fit resulting from [12]). At the bottom panels the sensitivity to the GPs is investigated.

nel [12] which was the primary goal of the experiment. A detailed description of the experimental arrangement and the parameters for all the measured setups are reported in [13]. The data acquisition time was optimized for the measurement of the π^0 channel and thus high statistical accuracy was not achieved for the photon channel measurements. The measurements were taken for $\theta_{\gamma^*\gamma} = 124°$ and $147°$, with $\theta_{\gamma^*\gamma}$ the polar angle in the c.m. frame between the initial and final photons of the VCS process, and for a range of azimuthal angles with respect to the electron scattering plane $\phi_{\gamma^*\gamma}$ from $215°$ to $316°$; extracting the A_h at different azimuthal angles is useful towards the understanding of the $\phi_{\gamma^*\gamma}$ dependence of A_h which is not known analytically. The kinematics of the present work compared to the ones of a previous similar measurement [6] is lower in Q^2 (0.20 $(\mathrm{GeV/c})^2$ instead of 0.35 $(\mathrm{GeV/c})^2$) and complementary in the range of the measured polar angles $\theta_{\gamma^*\gamma}$ since the present measurements were performed at backward angles while the previous ones [6] were taken at forward $\theta_{\gamma^*\gamma}$ (from $2.6°$ to $33.7°$).

The measured beam-helicity asymmetries A_h are presented in Fig. 3. Both the statistical and the total experimental uncertainties are exhibited. The results are dominated by the statistical uncertainties since the data acquisition time was optimized for the measurement of the π^0 channel which is characterized by a much higher count rate. The systematic uncertainties are driven mainly by the uncertainty of the central momenta and the spectrometer angles as well as from the uncertainty introduced to the final results by the variation of the analysis cuts. The central momenta and spectrometer angle uncertainties were varied in the analysis procedure in order to quantify the corresponding uncertainties. The deviations introduced to the extracted values of A_h resulting primarily from the variation of the size of the kinematical phase space bins (polar and azimuthal angles, invariant mass and four-momentum transfer), and of the coincidence-time and missing-mass analysis cuts were quantified as the corresponding analysis cuts systematic uncertainties. A cut on the target length is also applied in the analysis to ensure the elimination of any contribution resulting from background processes coming from the target walls. Detector inefficiencies and dead-times are canceled out in the asymmetry. Moller polarimeter measurements provided the measurement of the longitudinal beam polarization with a relative uncertainty better than 2%; this uncertainty results to a corresponding

systematic uncertainty to the A_h. In order to extract the final A_h result a theoretical model has to be used to project the finite phase space to point kinematics; for this part the DR [8, 9] model was used. The projection introduces a corresponding uncertainty due to the uncertainty of the description of the theoretical model but this uncertainty is rather small, at the order of $\approx 0.1\%$ in absolute magnitude for the extracted asymmetries. Radiative corrections [14, 15] have also a negligible effect to the asymmetry. The overall systematic uncertainties, for all of the experimental points, are approximately 50% of the corresponding statistical uncertainty.

The results are compared to the predictions of the DR [8, 9] calculation as exhibited in Fig. 3. The DR calculation is found to describe successfully the data, although the experimental errors are rather big. The A_h has been extracted at various $\phi_{\gamma^*\gamma}$ angles thus providing the opportunity to explore its azimuthal angle dependence which is not known analytically. The data support a $sin\phi_{\gamma^*\gamma}$-like dependence as expected from the pure VCS contribution in the numerator of the asymmetry. The sensitivity of the DR calculation to both the πN amplitudes and to the GPs of the proton is also explored (top and bottom panels of Fig. 3, respectively). The default DR calculation is using the MAID πN amplitudes; the calculation is also presented with the values of the three $N \rightarrow \Delta$ resonant amplitudes re-fitted utilizing the π^0 channel measurements [12] at the same kinematics. As exhibited in Fig. 3(a) and Fig. 3(b) the sensitivity to the resonant amplitudes is quite small. A re-fit including also the S_{0+} amplitude, in addition to the three resonant ones, was also performed; the sensitivity to the S_{0+} amplitude is provided through the fifth-structure function σ'_{LT} measurements of the π^0 channel [12]. Although this re-fit differentiated significantly the value of S_{0+}, the result of the corresponding DR calculation practically coincided with the DR calculation utilizing only the resonant amplitudes re-fit. The DR sensitivity to the GPs has also been explored as exhibited in Fig. 3 (panels (c) and (d)). The DR calculation has been explored by applying a rather small variation of $\pm$ 0.1 to the Λ_α and Λ_β (the two parameters related to the dipole electric and magnetic GPs respectively) with respect to the central corresponding values of 0.7 and 0.5. It is evident that the A_h offers a much higher sensitivity to the GPs compared to the πN amplitudes. The highest sensitivity is exhibited to the electric polarizability. Nevertheless, the uncertainty of the data is rather big to allow us to significantly constrain these parameters. The fact that our uncertainties are driven by statistical errors is suggesting that future dedicated measurements of higher statistical precision will be able to offer strong constraints to the electric polarizabilitiy, at the present kinematics. It is quite interesting that the interplay of the amplitudes to the GPs is quite different in the present measurement compared to a previous measurement of A_h [6] at different kinematics; the previous results [6], which are at higher Q^2 kinematics and at forward polar angles, exhibit higher sensitivity to the πN amplitudes compared to the GPs.

In conclusion we have performed measurements of the beam-helicity asymmetry A_h for virtual compton scattering in the $\Delta(1232)$ region accessing a new lowest Q^2. The experimental results, which provide access to the imaginary part of the VCS, have tested the DR formalism for VCS, where the imaginary part of the VCS amplitude is connected through unitarity to the $\gamma^* \rightarrow \pi N$ amplitudes, and we have found that the calculation is in good agreement with the data which show, although within rather large uncertainties, a $sin\phi_{\gamma^*\gamma}$ dependence of the A_h. The sensitivity to both the GPs and to the πN amplitudes has been explored, while also taking into account the simultaneously measured pion electro-production channel at the same kinematics, and the greatest sensitivity is exhibited to the generalized electric polarizability α_E. It is suggested that future A_h measurements of higher statistical precision that will explore a wide range of the $[Q^2,\theta_{\gamma^*\gamma}]$ phase-space can offer new valuable input towards a more complete description of the GPs of the proton and of the πN amplitudes.

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